

ANISOTROPY IN THE MICROWAVE SKY: RESULTS FROM THE FIRST FLIGHT OF BAM

G. S. TUCKER¹, H. P. GUSH, M. HALPERN, I. SHINKODA

Dept. of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1,
Canada

Electronic mail: gtucker@cfa.harvard.edu

and

W. TOWLSON

Dept. of Physics and Astronomy, University College London, London WC1E 6BT, England

Received _____; accepted _____

¹Current address: Harvard-Smithsonian Astrophysical Observatory, 60 Garden Street,
Cambridge, MA 02138

ABSTRACT

Results are reported from the first flight of a new balloon-borne instrument, BAM (Balloon-borne Anisotropy Measurement), designed to search for cosmic microwave background (CMB) anisotropy. The instrument uses a cryogenic differential Fourier transform spectrometer to obtain data in five spectral channels whose central frequencies lie in the range 3.7 cm^{-1} to 8.5 cm^{-1} . The spectrometer is coupled to an off-axis prime focus telescope; the combination yields difference spectra of two regions on the sky defined by $0^\circ 7$ FWHM beams separated by $3^\circ 6$. Single differences obtained at ten sky positions show statistically significant fluctuations. Assuming Gaussian correlated anisotropy, for the band average 3.1 cm^{-1} to 9.2 cm^{-1} , one finds $\Delta T/T = 3.1_{-1.1}^{+3.1} \times 10^{-5}$ (90% confidence interval) for a correlation angle of $1^\circ 2$. This corresponds to $Q_{\text{flat}} = 35.9_{-6.3}^{+17.7} \mu\text{K}$ (1σ).

Subject headings: balloons – cosmology: cosmic microwave background – cosmology: observations

1. INTRODUCTION

Observations of cosmic microwave background (CMB) spatial anisotropy at intermediate angular scales provide critical information on conditions in the early universe at redshifts $z > 1000$, and put strong constraints on cosmological scenarios. In particular, measurements at degree angular scales provide a sensitive test of scale free fluctuations below the so called Doppler peak (White, Scott & Silk 1994).

On an angular scale of 10° , the Cosmic Background Explorer (COBE) satellite has detected anisotropy of $30 \pm 5 \mu\text{K}$ (Smoot et al. 1992). Cross correlation with FIRS, an independent observation at much shorter wavelengths (Ganga et al. 1993), confirms the COBE observation and its interpretation as cosmic in origin. White, Scott, & Silk (1994) provides a recent summary of measurements in this field. We report here the first results from a new instrument, BAM (Balloon-borne Anisotropy Measurement), which measures at angular scales from $3/4$ to several degrees, angles just larger than typically predicted for the location the first Doppler peak. Measurements at this scale will determine the angular spectral index of primordial inhomogeneities.

2. APPARATUS

BAM consists of a cryogenic differential Fourier transform spectrometer coupled to an off-axis prime focus telescope. The advantages of the BAM approach to measuring CMB anisotropy, consisting of a clean optical system and good spectral coverage, have been described elsewhere (Halpern et al. 1995; Halpern et al. 1993). The spectrometer (Gush & Halpern 1992) was previously used for a measurement of the CMB spectrum (Gush, Halpern & Wishnow, E. 1990). For this experiment, the spectrometer is fitted with new input optics and passband-limiting filters, a new long duration ^3He refrigerator (Tucker

et al. 1996) and is housed in a new cryostat. The telescope is pointed with a three-axis servo system locked to guide stars. The electronic and electromechanical components of a pointing system used previously with other balloon-borne instruments (Anderegg et al. 1980) were incorporated into a new lightweight balloon gondola.

The two input collimators of the differential spectrometer view the same portion of the aluminum primary mirror, resulting in two input beams on the sky which are $0^\circ.70 \pm 0^\circ.05$ FWHM separated by $3^\circ.60 \pm 0^\circ.05$. The optical arrangement is sketched in Figure 1. Particular attention is paid to the suppression of spurious radiation entering the instrument. A diffraction control horn surrounds the two spectrometer entrance windows so that neither window is visible from anywhere except in reflection off the primary mirror. A reflective ground shield surrounds the entire lower portion of the instrument so that no part of the diffraction control horn, input collimators, or primary mirror is directly illuminated by radiation from the earth.

The interferometer has two independent bolometric detectors, one for each output port. Each bolometer yields a double sided interferogram proportional to the brightness difference between the two input beams. The scanning time for one interferogram is 0.67 s, and the optical path length difference runs from 1.44 to -0.91 cm. Spectra are obtained *a posteriori* by Fourier transforming these interferograms.

3. FLIGHT

BAM was launched from the National Scientific Balloon Facility in Palestine, Texas at 00:45 UT (at sunset) on 8 July 1995 and reached a float altitude of 41.5 km at 05:00 UT. Observations ended at 09:00 UT, in darkness, when the payload was near the end of telemetry range and the flight was terminated. The payload was recovered with only minor

damage.

To calibrate the instrument and measure the beam profile, three scans of the telescope beams across the planet Jupiter were made just prior to reaching a stable float altitude. The scans were made in azimuth at three fixed elevation angles, so that Jupiter passed through both beams of the telescope. Unfortunately, the elevation angles were not chosen optimally so Jupiter was scanned only with the lower half of the telescope beams. As a result the maximum possible signal from Jupiter was never realized. Using data about the beam shape obtained on the ground prior to flight, along with the flight data, it is estimated that the maximum observable signal is 1.2 ± 0.1 times larger than the measured response. The data of Griffin et al. (1986) for Jupiter have been used as an absolute reference to calibrate the power sensitivity of the instrument. The total calibration uncertainty is 20%.

Soon after reaching float altitude, an integrated circuit on board the telescope pointing system failed. This caused disruption of commands controlling the telescope orientation. The telescope remained locked to guide stars, but slewing the telescope to new orientations could not be carried out on the planned schedule. After diagnosing the problem, a switch was made to a redundant telemetry channel not originally intended to be used for in-flight control; and a software patch was also developed. Thus, reliable operation of the pointing system was re-established for the last half hour of flight. The instrument performed well despite these problems, but the reduction of observing time reduced the sensitivity, and the disruption of the planned observing pattern limited the ability to check for atmospheric effects.

As this was the first flight of BAM, a conservative observation strategy was adopted to allow the instrument performance to be understood. The telescope observes near the meridian above the North Celestial Pole. The left telescope beam is moved to a target spot east of the meridian and the telescope is locked with reference to a guide star within 5° of

the beam. A series of single difference interferograms, I_i^+ , are obtained while tracking the guide star. After a period of observation, called a stare, the telescope is slewed so that the right beam is on the target spot and a second series of interferograms, I_i^- , is accumulated. The series I_i^+, I_i^- is called a wobble. The difference signal $I^+ - I^-$ is an interferogram of the difference in brightness between the target spot and the average of the two spots to either side of it. Wobbling is repeated while tracking the target spot to west of the meridian after which a new target spot east of the meridian is acquired. It had been intended to initiate a new stare every three minutes, but the command intermittency resulted in not wobbling for periods of up to fifteen minutes in duration.

4. DATA ANALYSIS

The data set consists of a series of three-minute long data files containing the bolometer and optical path length difference signals sampled uniformly in time along with 50 channels of auxiliary data. Each file contains approximately 263 interferograms. About 10% of the data in each interferogram is deleted corresponding to the time that the interferometer mirror is slowing and reversing direction at the ends of the scan. Because the bolometer signals are sampled uniformly in time and the interferometer speed is not constant, it is necessary to perform an interpolation of the data to acquire interferogram samples uniformly spaced in optical delay.

These interpolated interferograms are edited as follows. Those interferograms corresponding to periods in which the telescope was slewing are deleted (23.2%). Data contaminated by the effects of cosmic rays striking the bolometers are removed from the remaining data using the following algorithm. For each stare, a mean and variance are computed at each value of optical delay in the interferogram. Any individual interferogram containing a point more than 5σ from the mean is excluded from further analysis; a total

of 6.7% of the data are deleted this way. To exclude smaller cosmic ray events which are hidden in the variance caused by the events removed above, the process is repeated on the remaining interferograms, and a further 2.0% of the data are deleted. After the above editing 61.4% of all the data remain for analysis. Spectra are calculated using an FFT routine to find the Fourier transform of each interferogram.

Interferograms obtained during ascent contain an appreciable atmospheric signal. These data are used to provide a reference for phase correcting the interferograms, that is, removing the effects of phase shifts in the bolometers and amplifiers. Thus, optical signals appear only in the Fourier cosine transform. The sine component of the phase corrected Fourier transform contains no optical data at any frequency but provides a monitor of systematic errors. Signals from the atmosphere at float altitude are too weak to provide a phase correction reference. An independent and consistent phase correction is obtained from the Jupiter data.

We had intended to analyze the data using a double difference technique taking data from temporally adjacent stares in the + and – positions. However, the unreliable wobbling achieved during flight precludes such an analysis. Therefore only single differences are analyzed. Each stare is divided into two half-stares. For each half-stare the difference spectrum $\Delta_i^\nu = \mathcal{F}(I_i - I_{\text{off}})$ is calculated where the + and – subscripts on the symbol I have been dropped since only single differences are being considered. The symbol \mathcal{F} indicates a Fourier transform, and I_{off} is a known constant offset interferogram due to radiation internal to the instrument. The magnitude of the offset is about 20 mK. The variances of the Δ_i^ν 's, $\sigma_{\Delta^\nu}^2$, are also computed and are an error estimate unbiased by sky signal; these error estimates are propagated through the remainder of the analysis.

During the flight, a gap in the anisotropy data of about an hour occurred while the software patch was being developed. During this time the telescope observed another part

of the sky, at a different elevation angle than for the data reported here. (Unfortunately, because wobbling was absent conclusions about anisotropies could not be drawn at this different elevation angle; the data were used, however, to help check for systematic errors.) The data taken before and after the gap are analyzed separately but identically. For each frequency channel the data are simultaneously fitted to a model of the sky, a constant offset, a linear drift in time, payload altitude, and the temperature of the torque motor which drives the spectrometer scan mechanism. The fits are done independently for the cosine and sine transforms and a full covariance matrix is propagated. The reduced χ^2 for the fits range between 0.37 and 1.20. In the worst frequency channel the total drift during the flight is 2.5 mK while in the best channel the drift is 500 μ K.

The torque motor just referred to is located in an ambient temperature region of the cryostat vacuum space. Approximately every 30 minutes by operator choice, a heater on the torque motor was turned on or off in order to maintain the motor temperature in a useful range. This power variation caused the motor temperature to vary by 4 K during the flight. Apparently heat conducted from the motor through the shaft to the mirror scanning mechanism differentially heated the interferometer housing. A significant drift (up to 600 μ K) correlated with the torque motor temperature is observed in the sine transforms but is not apparent in the cosine transforms. Since light emitted from the interferometer walls is modulated differently from light entering the interferometer through the input collimators, it is plausible that such a signal would only appear in one phase of the transforms, as observed.

In addition to the torque motor temperature, a number of other temperatures and differential temperatures are measured both inside the cryostat and elsewhere on the gondola. With the exception of the torque motor temperature, no correlation between Δ^ν and any temperature or differential temperature is observed. In particular, a 2 K

temperature gradient was induced across the primary mirror near the end of the flight by heating one side of the mirror. No correlation is observed between Δ'' and the temperature of the primary mirror or temperature gradient across the mirror.

Due to the limited integration time and failure to obtain a sufficient number of *double* differences, the sensitivity achieved in each frequency channel is modest and inadequate to accurately constrain the spectral index of any observed signal; therefore we present only band average data. The final single differences are shown in Figure 2.

If each stare is divided instead into thirds, the analysis yields consistent results. However with finer subdivision, the final differences are discrepant indicating the presence of a non-stationary noise source. The cross elevation of the telescope oscillates with a peak-to-peak amplitude of $0^\circ.4$ and a period of 12 s. This may be the source of the non-stationary noise. However, the sensitivity on these very long time scales is low and it has been impossible to find and remove any correlation. Another problem which gave concern is that there is increased noise in the detectors when the interferometer mirror is scanning; however, there is no evidence that this has introduced systematic effects that could mimic a detected signal.

5. LIMITS ON CMB ANISOTROPY

There is strong evidence that the observed signals are from optical sources external to the instrument. Significant power is detected only in the cosine component of the spectrum, which contains optical signals, while the sine component, which does not contain optical signals, is consistent with noise. Given the limited integration time, we can not reliably dismiss the possibility that the signal is from the atmosphere. It is also difficult to rule out definitively earthshine and moonshine entering the instrument differentially although

much care has been exercised in designing the ground shield. There appears to be a mild correlation between the cosine and sine single differences (consisting of a monotonic drift in offset during the flight). The cause of this possible correlation is unknown. Because the power in the correlated part of the signal does not exceed the power in the sine component, and the power in the sine component is negligible, it can be concluded that the small correlated component has minimal effect on the detected power in the cosine component. The structure in Figure 2 does not correlate with the IRAS 100 μm maps (Wheelock et al. 1993).

Assuming that CMB anisotropy is Gaussian correlated with a correlation angle θ_c , a likelihood analysis (Readhead et al. 1989) has been performed on the full frequency band data. For a given θ_c , the 90% confidence interval on $\Delta T/T$ is computed by integrating the resulting likelihood curve. The results are shown in Figure 3. A value $\Delta T/T = 3.1_{-1.1}^{+3.1} \times 10^{-5}$ at a coherence angle of $\theta_c = 1^\circ 2$ is derived; the calibration uncertainty is not included in this number. For the sine component of the spectrum a null signal is expected. Applying the same analysis to the sine component, a signal consistent with zero is found; a 95% upper limit of $\Delta T/T = 1.89 \times 10^{-5}$ is found for $\theta_c = 1^\circ 2$. This is a measure of the instrumental sensitivity. In particular, the signal associated with any correlation between the sine and cosine components shown in Figure 2 is not larger than the full sine amplitude, and thus is consistent with zero and not consistent with the power detected in the cosine component.

Using the approximations of Steinhardt (1995) and White & Scott (1994), the detected cosine amplitude can be expressed as $Q_{\text{flat}} = 35.9_{-6.3}^{+17.7} \mu\text{K}$ where the effective spherical harmonic of the observation geometry is $\bar{\ell} = 74$.

6. CONCLUSION

Statistically significant fluctuations in the microwave sky have been observed. However, the spectrum has not been measured with sufficient sensitivity to attribute these fluctuations definitively to cosmic origin. On the other hand the new results are similar to those of others measuring anisotropies; that is, there are scattered regions of the sky whose temperatures are unexpectedly high. Clearly, it is becoming urgent to establish whether these regions pertain to the cosmic background. This new instrument, BAM, is potentially capable of doing this in a full flight, since it measures the spectrum of the anisotropies.

Without pointing system problems and a longer balloon flight, an increase of 4–8 in integration time is easily achievable. In addition another factor of 2–4 in reduced detector noise is easily realizable with a new mirror scanning mechanism. We expect to adopt a more optimal observing strategy and spectral resolution for the next flight.

We would like to emphasize that the modest sensitivity obtained in this flight is the result of a series of mechanical and electrical malfunctions and is not the result of any fundamental limit of the instrument. In addition all of the malfunctions have readily identifiable causes. Preventing a recurrence of these malfunctions provides no serious technical challenges.

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Fig. 1.— Optical layout of the off-axis telescope. In the side view to the right the short dash line shows the optic axis of the off-axis parabolic primary mirror. The optic axis passes through the location of the input collimators at the focus of the primary mirror. The long dash lines indicate the extreme rays accepted by the input collimators. On the left is shown the telescope as viewed from the front. The two input collimators are displaced laterally from the focus and are tilted to view the same portion of the primary mirror resulting in the beam pattern shown at the top. The dotted line indicates the height of the ground shield

Fig. 2.— Final single differences and statistical error bars for the ten positions in right ascension at a declination of about 70° . The \bullet symbols denote results for the cosine component of the spectrum which contains the optical signal. The \times symbols indicate the sine component of the spectrum which represents noise. The sine symbols are offset in right ascension for visual clarity. There is significantly more power in the cosine than sine component indicating that a signal has been observed.

Fig. 3.— Limits on CMB anisotropy assuming Gaussian correlations with correlation length θ_C . The solid curves show the peak of the maximum likelihood function and the 90% confidence interval for the cosine component of the spectrum. The dashed lines show the maximum of the likelihood function and the 95% upper limit on the sine component of the spectrum. Zero power can not be ruled out for the sine component.





